

**OPTIMIZATION OF HETEROGENEOUS
UTILIZATION OF THORIUM IN PWRs TO ENHANCE
PROLIFERATION RESISTANCE AND REDUCE WASTE**

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EXECUTIVE SUMMARY

Research Objectives

This work examines heterogeneous core design options for the implementation of the Th-²³³U fuel cycle in pressurized water reactors (PWRs) without reprocessing or recycling. It identifies the core design and fuel management strategies which will maximize the benefits from inclusion of thorium in the fuel. The assessment concentrates on key measures of performance in several important areas, including proliferation characteristics of the spent fuel, reliability, safety, cost, environmental impact, and licensing issues. The focus is on once-through fuel cycles that do not involve reprocessing of the spent fuel. A 193-assembly Westinghouse reactor utilizing 17x17 fuel is taken as the model core.

One design, the Whole Assembly Seed and Blanket (WASB) concept, provides seed units and blanket units which separately occupy one full-size PWR assembly each, and the assemblies are arranged in the core in a modified checkerboard array (Figure-1).

The second design, the Seed-Blanket Unit (SBU), also known as the Radkowsky Thorium Fuel (RTF) concept, aggregates the thorium blanket and the uranium seed into subassembly units such that a complete seed-blanket unit is a one-for-one replacement for a conventional PWR fuel assembly (Figure-1).

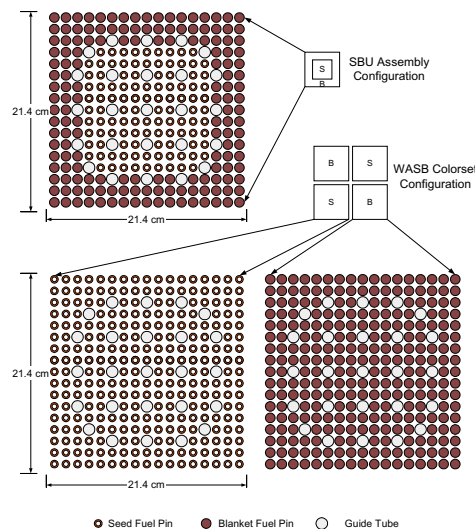


Figure-1 SBU and WASB Fuel Assembly Design

The studies for both approaches have (1) identified the core design and fuel management strategies that maximize the benefits from inclusion of thorium in the fuel and (2) extended the analyses to validate the results over a range of possible operating conditions.

Research Achievements

Two separate designs, SBU and WASB, have been developed which significantly improve the intrinsic proliferation resistance and waste characteristics of PWR fuel while achieving 18 month cycles. The total production of plutonium is reduced by a factor of about three and the volume of spent fuel by a factor of about two and a half relative to a present-day commercial PWR. Furthermore, the plutonium that is produced is of inferior quality for potential utilization in weapons: it has a higher heat generation from increased Pu-238 and a stronger spontaneous neutron source from an increased percentage of Pu-238, Pu-240, and Pu-242. Both designs have been checked from the neutronic and thermal hydraulic points of view, and a limited set of safety and fuel performance examinations were performed. Despite their somewhat different implementations, the two designs provide similar performance characteristics. It was concluded that there are waste volume advantages and plutonium reduction advantages, while maintaining the essential neutronic and thermal safety performance of current PWRs. There is no economic advantage to this fuel cycle under the present economic conditions as the fuel cycle cost of either the SBU or WASB approach is comparable to that of present PWRs. However, any increases in the prices for storing and handling spent fuel and/or reduced prices for uranium enrichment may change this conclusion. This fuel also requires special design and manufacturing capabilities to produce high burnup annular fuel pellets to be used in the seeds. Significantly, both approaches utilize assembly designs based on a Westinghouse 17x17 assembly where the sole modification is in the details of the fuel rods and the grids. Therefore, in principle, they are both retrofittable into existing PWRs with little or no modification.

Specific achievements in the course of this NERI project are summarized below and are applicable to both SBU and WASB unless stated otherwise. The SBU development, which is an improved version of Radkowsky's RTF, has been done primarily by BNL with support from Ben Gurion University. It is closely related to an ongoing project under the DOE Initiatives for Proliferation Prevention program and private funding which is focused on RD&D activities in Russia and the West. The initial reference point for the SBU optimization studies is based on the results for the PWR from that study. The WASB development has been done primarily at MIT.

1) Mechanical designs were developed for both seed and blanket fuel assemblies within the constraints of the Westinghouse 17x17 design (assembly envelope, rod pitch, guide tube locations). Both SBU and WASB designs utilize solid thorium/uranium oxide pellets for the blanket, and annular uranium oxide pellets for the seed. In both cases the flow resistance of their grids has been increased to enhance coolant flow into the higher power seed region. For the WASB design the outer diameter of the blanket fuel rods has also been increased to increase the flow in the seed assemblies. The SBU design permits refueling by inserting and removing individual seed rods with a machine similar to one used to replace failed fuel rods. The WASB design allows whole seed assemblies to be removed individually. In either approach the upper and lower end-fittings can be identical to those currently employed. The final SBU design results in 108 of the 264 fuel rods in each assembly being seed rods, amounting to 41 % of all the fuel rods in the core. By comparison, with the WASB design,

84 of the 193 fuel assemblies are seed assemblies so that 43.5% of the fuel rods in the core are seed rods, quite similar to the SBU design.

2} During the mechanical design of the assemblies, the neutronic designs were optimized to maximize breeding and fission of ^{233}U in the blanket and to minimize production of Pu in the seed (where almost all the Pu is created). The adequacy of the deterministic lattice physics codes (BOXER and DRAGON for SBU and CASMO for WASB) in the highly heterogeneous situations characterizing seed-blanket cores, was verified by comparison with continuous energy Monte Carlo codes (MCNP and RECOL for SBU and MCNP for WASB).

3) Viable 18 month cycle core designs and fuel management plans were developed. Both SBU and WASB utilize 3 batch fuel management for the seed - i.e., 1/3 of the seed fuel is replaced every 18 months. Single batch fuel management is used for the blankets, with SBU blanket fuel remaining in-core for 6 cycles and WASB blankets for 9 cycles.

4) Acceptability of the neutronic aspects of the core designs was checked at nominal operating conditions via calculation of power distributions, radial and axial peaking factors, reactivity coefficients and control rod worths. The cycle energy and reactivity coefficients of both SBU and WASB designs are similar to those of conventional PWRs. Radial peaking factors in the seed fuel are significantly above those of conventional PWRs, but this has been compensated for in the designs by the higher flow provided in the seed regions. See items 1, 5 and 6 in this list for further discussion. Control rod worths are smaller than those of conventional cores and may require either reconfiguration of the control banks or redesign of the control rodlets themselves with a more highly absorbing material such as enriched B4C.

5) Acceptability of the thermal hydraulic aspects of the core designs to accommodate AOO (Anticipated Operational Occurrence) conditions was estimated by verifying adequate margin to centerline melt and to DNB using static calculations at 112 to 118% of nominal thermal power, the range of typical thermal power attained in this class of transients. These calculations were performed using conservative temperature and pressure input assumptions in one-eighth core models, with individual sub-channels represented in the hot assembly and lumped models for the remainder of the assemblies. These calculations used the W-3 correlation with COBRA-EN for SBU and VIPRE for WASB.

6) A sampling of preliminary safety analyses showed that both the SBU and WASB designs gave acceptable results for large-break loss of coolant accidents (LOCA), loss of primary flow (LOPF), and loss of off-site power (LOOP) transients. Following the LOCA, the maximum clad temperature in the seed exceeds the maximum temperature of a homogeneous UO_2 core, but remains well below the limit of 1200 C. All calculations included representations of average seed and blanket and hot seed areas in the core. Calculations were performed with RELAP5-3D for SBU and with MARS, a Korean adaptation of RELAP5, for WASB.

7) Spent fuel characteristics evaluated for both designs with the ORIGEN code show marginally less activity from the seed-blanket spent fuel in the near and medium term and somewhat more in the long term. However the increase occurs on the order of 100,000 years

in the future, when the total activity and heat generation have decayed to quite low levels. It is due to decay of daughter products of thorium.

Formally, the Russian Research Center – Kurchatov Institute, and several organizations participated in the collaboration. However, since the work in Korea and Russia was performed for significantly different reactor configurations (CE-System-80 and VVER-1000, respectively), and under different assumptions for the fuel cycle, their results are not included in this report.